

# Faster Communication Using Probabilistic Swapped-Bell-States Analysis

Hauke Traulsen

Computer Scientist at The Fraunhofer Institute for Integrated Circuits IIS, Nordostpark 93, 90411 Nuremberg, Germany

*This article was written by the author outside of his regular charges.*

---

## Abstract

In this article, a procedure called Probabilistic Swapped-Bell-States Analysis (PSBA) is proposed. Using this procedure two communication partners can transmit (binary-encoded) information over large spatial distances. This procedure is unusual insofar as no classical communication channels are used either during or after information encoding. To make this possible, entanglement swapping is used as a transport channel. The encoding of bits is realized by the execution (or non-execution, as the case may be) of entanglement swapping on multiple photon pairs, while decoding is realized by a statistical detection of swapped entanglements. If the PSBA procedure sustains itself against a rebuttal by the scientific community, it would constitute a technical approach for transmitting information faster than light. The PSBA procedure seems to be in harmony with the no-communication theorem, since PSBA does not manipulate (and teleport) specific states from one (entangled) particle to another in order to communicate, but instead uses statistics on entanglement swappings for information encoding.

**Keywords:** Entanglement, entanglement swapping, communication, Bell-state analysis

---

## 1. Introduction

Entanglement is one of the fundamental concepts of quantum mechanics. Albert Einstein called this kind of correlation ‘spooky’ [1], as it can be shown that manipulations on one constituent of an entangled pair of particles affect the other constituent very fast: Considering an unknown kind of interaction between both particles, this transmission would have to be executed at a speed at least 10,000 times faster than light [2]. There would be unprecedented opportunities if this ‘instantaneous’ influence could be used for sending messages. However, as the no-communication theorem explains, this kind of influence cannot be used for communication [3]. Fortunately, the no-communication theorem allows for the detection of whether two photons are entangled or not, and it does not prohibit the creation and destruction of entanglements by entanglement swapping. With these thoughts we turn towards the basic concept of PSBA.

## 2. Basic Concept

With the well-known procedure called “entanglement swapping” it is possible to entangle two photons, even though they have never interacted with each other [4, 5]. The concept of a special variant of entangle swapping, taken from [6], is shown in Figure 2 on the following page:

A pair of polarization-entangled photons (1&2) is produced at Alice’s location; another pair (3&4) is produced at Bob’s location. Alice sends one photon (2) to Victor. Bob does the same (photon 3). Alice and Bob measure the polarization of the photons 1 (Alice) and 4 (Bob). Victor decides randomly whether he measures the polarization of his photons (2&3) by a separable-state measurement (SSM) or by a Bell-state measurement (BSM). If he uses the Bell-state measurement, the entanglements of 1&2 and 3&4 will be eliminated, and new entanglements of the photons (2&3) and (1&4) will be created. As shown in Figure 2 on the next page and shown and described in [7], an entanglement swapping can occur even if the measurements of Alice and Bob occur *before* Victor makes his decision. But this ‘back-in-time’ effect is not the main subject of this article. What we need in this article is the basic mechanism of entanglement swapping, but we will still discuss this delayed-choice variant of entanglement swapping later in this article.

This article is inspired by two experimental result diagrams shown in Figure 3 of [6]. A sketch of these diagrams is shown in Figure 1 on the following page. As in the delayed-choice experiment described, Victor’s decisions (BSM or SSM) were completely random. This randomness implies a required sorting (based on Victor’s choices) of Alice’s and Bob’s detected correlations into at least two subsets: correlations for Victor’s BSM (left part of the diagram) and correlations for Victor’s separable-state measurement (right part of the diagram). The author asked himself (as those two diagrams look quite different):

---

Email address: hauke.traulsen@iis.fraunhofer.de  
(Hauke Traulsen)

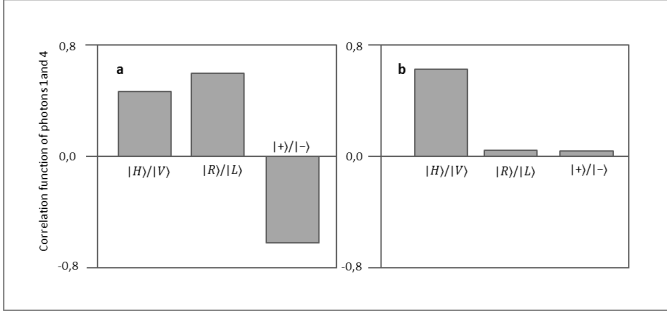


Figure 1: Sketch of Figure 3 in [6]: signatures *a* and *b* for correlations of photons 1 and 4. Situation for *a*: Victor used Bell-state measurement. Situation for *b*: Victor used separable-state measurement. To generate these diagrams measurement data from Victor, Alice and Bob is needed, but - under certain conditions (see text) - distinguishable diagrams can be generated without additional classical communication between Victor and (Alice/Bob).

If it's possible to generate these two diagrams by sorting data produced by random decision, would it not be possible to generate these diagrams deliberately? What would happen if Victor decides not randomly, but deliberately for BSM and produces entanglement swappings (let's say, for example, 300 times in sequence)? Would we see something like the left diagram in Figure 1? And if Victor decides (again 300 times in sequence) to measure the photons individually and we count coincidences as described before: Would we see something like the right diagram? The author assumes that this would be the case and the rest of this article is based upon this assumption. If we detect something like 'the left diagram' (entanglement swappings), we want to interpret this as a sent binary 1 (1b). If we detect something like 'the right diagram' (SSM), we want to interpret this as a binary 0 (0b). In this article, we will use an approach for distinguishing a sequence of maximally polarization-entangled photons and a sequence of unentangled photons without necessarily distinguishing any of the Bell states unambiguously. It will be shown that no information from Victor is required to decide probabilistically whether a sequence of photon pairs (shared by Alice and Bob) is either maximally entangled or unentangled.

But let us go one step back and construct the PSBA concept from the bottom up. First of all, the suggested PSBA procedure should be interpreted as a gedankenexperiment due to a lack of technical capabilities to transport entangled photons over long spatial distances and to store entangled photons over a longer period of time, whereas proof-of-concept experiments should be realizable today by using existing technologies. The latter assumption is reasonable, since the setup of such a proof-of-concept experiment will have significant similarity to experiments already realized [5, 6, 8, 9]. We start the setup of this gedankenexperiment by creating two pairs of maximally polarization-entangled photons (1,2) and (3,4) as also shown in Figure 2. To generate these photon pairs, Spontaneous Parametric Down Conversion [10] can be used. In contrast to the system architecture assumed for Figure 2 in the

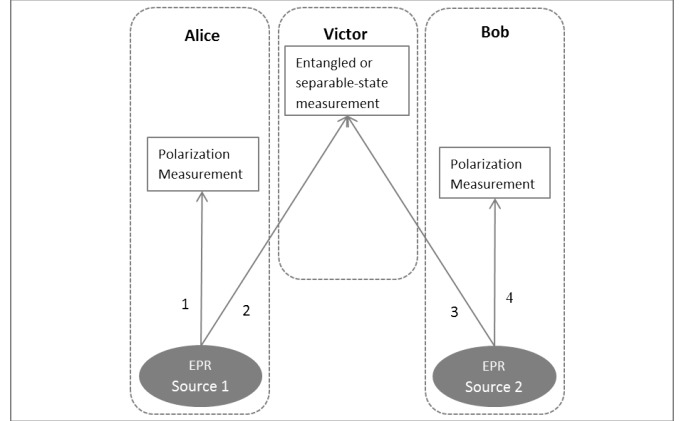


Figure 2: Concept of a time-delayed entanglement swapping experiment, taken from [7]

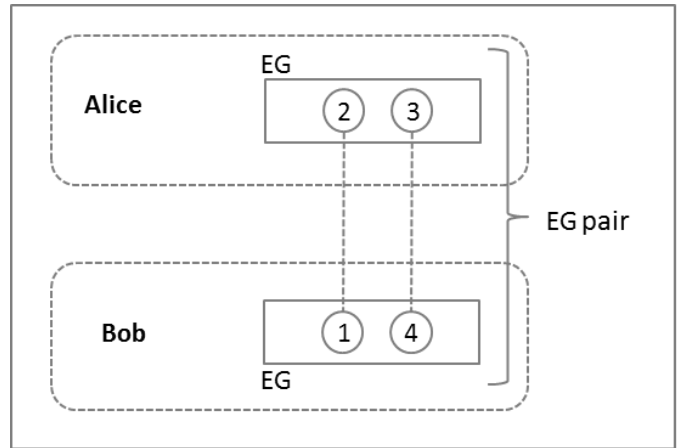


Figure 3: Basic concept of entanglement groups (EG): A pair of entangled EGs:  $EG_A$  (at Alice) contains photons 2 and 3 which are maximally polarization-entangled with photons 1 and 4 in  $EG_B$  (at Bob). The entanglement is shown by the dotted lines between the photons.

PSBA concept, *both* photons 1 and 4 are sent to Bob, while Alice gets the photons 2 and 3. We assume Alice and Bob can store their entangled photons until they are needed for communication. A third participant (Victor) is not needed, as Alice assumes Victor's role. We name the photon pairs 2&3 and 1&4 "entanglement groups" (EG). Without any loss of generality, we study the case with *two* particles per entanglement group, while future applications with more particles per EG are imaginable. Together we will call those two EGs at Alice and Bob an "EG pair". Figure 3 shows the EG concept schematically. The EG concept is the central architectural component of the PSBA procedure.

Alice acts as the sender, Bob as the receiver. In order to send a single bit, Alice decides how she will measure her photons 2 and 3: Either she performs a Bell-state measurement (BSM) and thus she entangles photons 1 and 4 at Bob (Entanglement Swapping), or she measures her photons 2 and 3 individually, which will not entangle photons 1 and 4 with each other. However, the BSM could bring

the photon pairs 2&3 and 1&4 unpredictably into one of four Bell states. Therefore, purposefully setting the type of the Bell state cannot be used for encoding information. All we seem to know is that entanglement swapping brings 2&3 and 1&4 into exactly the *same* unknown Bell state [5, 11]. We can not use the type of swapped Bell states for encoding, but we can use the fact that the photons 1&4 are *in one of the four Bell states (it does not matter which one)* for encoding. If we could detect that the photon pair 1&4 is probably entangled, this would be sufficient for encoding. In the meantime, there are several efficient technical approaches for detecting even more than two of the four Bell states on an analyzed photon pair [8, 9]. In particular, the fermionic behavior of two photons 1 and 4 in the Bell state

$$\Psi_{14}^- = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle - |V\rangle|H\rangle)$$

at a beam splitter as opposed to the bosonic behavior of the other three Bell states would be of great benefit. Two probably possible setups for distinguishing a sequence of maximally polarization-entangled photon pairs from a sequence of unentangled photon pairs are shown in Figure 4. One of them (setup *b*) uses the said detection of the Bell state  $\Psi^-$  (as a simplified version of setup *b*, shown in Figure 7 on the following page).

As described above, with just one photon pair Bob will not be able to decide with sufficient certainty whether Alice has performed BSM or SSM. But a statistical evaluation of correlation tests (as described in Figure 4) on a larger sequence of EGs could help Bob out: As described above, the author assumes that Bob can count coincidences and can construct one of two characteristic correlation diagrams: A characteristic and significant mixture of detected correlations (we are not necessarily interested in identifying particular Bell states) will lead to the certainty Bob needs to determine whether Alice has performed multiple BSMs or multiple SSMs.

Therefore, in preparation for their PSBA communication, Alice and Bob share a ‘sufficiently’ large number of EG pairs with each other and pay attention to the same order of the EGs. Alice and Bob each henceforth have a sequence of EGs (EG1, EG2, ...) at their disposal. Furthermore, Alice and Bob have to determine a parameter  $r_C$  ( $r$  for ‘reliability’,  $C$  for ‘channel’) for their PSBA channel by testing: How many photon pairs (EGs in sequence) have to be entangled by BSM at Alice before Bob can detect the transmitted value 1b with sufficient certainty? (Alice and Bob stipulate a concrete probability  $p$  for the term ‘sufficient certainty’.) The value of  $r_C$  may be high as long as it is finite. After determining  $r_C$ , both Alice and Bob partition their EG sequence in EG blocks with  $r_C$  EGs each. We refer to those blocks as SCGs (statistical correction groups). Figure 5 shows the SCG concept schematically.

Consequently, Alice and Bob now each have a sequence of SCGs at their disposal. In order to transmit a single bit (0b or 1b), Alice and Bob use one SCG pair per

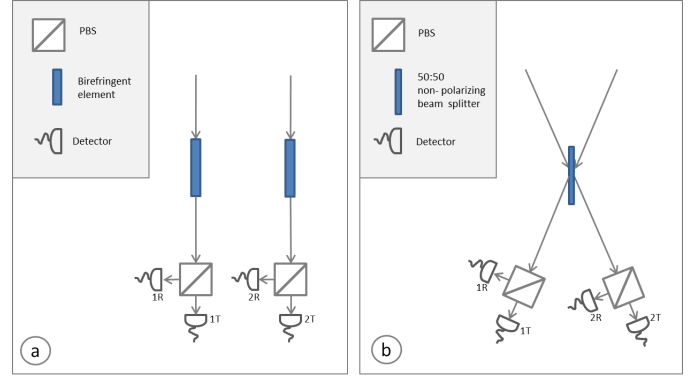


Figure 4: a: Statistical distinction of either maximally polarization-entangled photons or unentangled photons: For  $\Psi^\pm$  states, the H and V parts of the wave function will be separated by strongly birefringent material (as used in [12]). Therefore the photons will be detected as time-separated. Photon pairs in  $\Phi^\pm$  (with no detection-time delay) should show identical behavior at the beam splitters, while photon pairs in  $\Psi^\pm$  should show exactly the opposite behavior. Uncorrelated photons (time-separated or not) should show no quantum correlation at the polarizing beam splitters. b: statistical detection of  $\Psi^-$  at a 50:50 non-polarizing beam splitter. Only  $\Psi^-$  entangled photons will be detected in different output ports of the non-polarizing beam splitter, while photons in one of the other three Bell states will end up in the same output port. For unentangled (distinguishable) photons we probably will not see the typical Hong-Ou-Mandel-Dip [13]. Of course, for unentangled and *indistinguishable* photons the author assumes a perfect HOM-Dip: Under perfect HOM conditions not one unentangled photon pair would be able to let its two photons emerge from different output ports of the 50:50 non-polarizing beam-splitter, while about 25 percent (swapped  $\Psi^-$  states) of the entangled pairs will be able to let their two photons emerge from different output ports. For a general discussion of the possible analysis results see Figure 7 on the following page

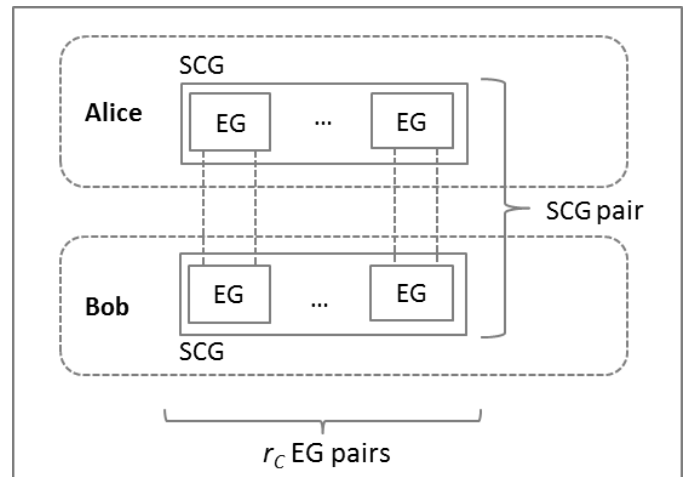


Figure 5: SCG concept: One SCG pair contains  $r_C$  EG pairs in sequence. To send the value 1b, Alice performs a Bell-state measurement on all photon pairs (EGs) in her SCG; to send the value 0b, Alice measures all of her photon pairs individually.

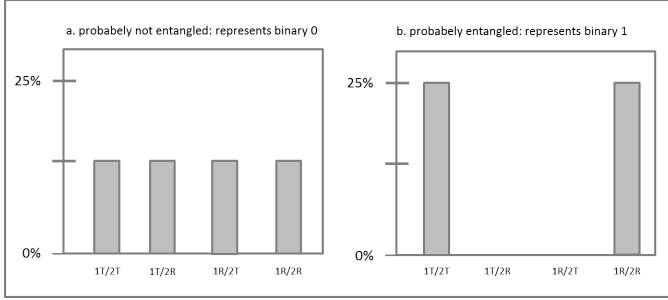


Figure 6: Correlation diagrams (theoretical/ideal results of the gedankenexperiment for the analyzer-setup shown in part (a) of Figure 4 on the previous page): The diagrams here show the correlations for  $\Phi^\pm$  only, but - as described above - Bob can distinguish  $\Phi^\pm$  and  $\Psi^\pm$  by time-delayed detections. So Bob can generate these diagrams without additional information from Alice. If all photon pairs in Bob's SCG are unentangled (and randomly polarized), Bob will find a correlation diagram similar to *a* (left). If all photon pairs are entangled in one of the four Bell states, Bob will find (for  $\Phi^\pm$ ) a correlation diagram similar to *b* (right). For the analyzer-setup shown in part (b) of Figure 4 on the preceding page: Finally, the author assumes a single non-polarizing 50:50 beam splitter as a sufficient setup for detecting a stream of (by entanglement swapping) entangled photon pairs (see Figure 7 for the discussion of this setup)

bit. For the next bit they use the next unused SCG pair in the SCG sequence. Each SCG pair can be used only once for a bit transmission, since after entanglement swapping (or SSM) the entanglements between Alice and Bob (as shown in Figure 5 on the previous page) will be dissolved. In order to send the binary value 1b, Alice executes a Bell-state measurement on every single photon pair (EG) of her current SCG; to send the value 0b, Alice performs separable-state measurements analogically. As a consequence of Alice's Bell-state measurements, every single EG (in the ideal case) in Bob's current SCG will be in a Bell state. Bob executes a correlation analysis (as described above) on every photon pair of his SCG. After doing so, Bob can determine with a sufficient probability  $p < 1$  whether his photon pairs (1&4) in this SCG were more likely to be unentangled (Bob reads 0b) or entangled with each other (Bob reads 1b). For the setup shown in part (a) of Figure 4 on the preceding page the author expects (under theoretical/ideal conditions) two correlation diagrams similar to those in Figure 6.

Hence Alice can transmit binary-encoded messages to Bob with sufficient certainty by using PSBA. For example, if Alice wants to send the message "FASTER" (in 8-bit ASCII Alice needs 6 bytes or 48 bits) to Bob, she uses 48 SCGs to encode this message. Bob should know the length of the message beforehand (i.e. he should know how many SCGs he has to analyze). Therefore, e.g. one byte (and therefore 8 SCGs) in front of the message data could be used as such a length field. In addition, before sending (encrypted) messages photons could be used for security by Quantum Key Distribution [14] (see discussion). As described above, for this transmission neither classical ways of communication were used in addition to quantum



Figure 7: The matrix of possible correlation proportions (left) for a simplified Bell-state analyzer setup (right): In order to allow indistinguishability, for the possible results (shown in the matrix) an identical time of arrival for the two photons at the beam splitter is assumed. The left part of each of the four given correlations proportions represents the statistically expected percentage of photon pairs with its photons detected at different exits of the beam splitter, the right part of each proportion represents the expected percentage of photon pairs with both photons leaving the beam splitter through the same output port. As described before, the swapped Bell-states (Alice sends 1b) will produce 25 percent of "two-exits-pairs" (by the  $\Psi^-$  states) and 75 percent of "one-exit-pairs" (case B) in the analysis. Case A should be a contradiction under the assumption of the same time of arrival at the beam splitter. When Alice sends 0b (and performs no entanglements swappings) the photons in the photon pairs in Bob's SCG are expected to be distinguishable (by polarization and/or frequency, case C). Therefore, Bob's analysis would generate a 50:50 proportion. The other (theoretically possible) case (D): All photon pairs in Bob's SCG are not entangled but indistinguishable (How this could be realized technically by Bob in a PSBA scenario seems to be questionable). In this case Bob could probably see a (theoretically perfect) HOM dip. However, in both 'unentangled cases' (C and D) the proportion would be significant different from the proportion 25:75 (produced by swapped Bell-states). Therefore, Bob can distinguish a SCG with photon pairs in swapped Bell-states from a SCG with unentangled photon pairs.

mechanisms, nor were (entangled) particles (photons) sent from Alice to Bob (or vice-versa) after information encoding. As the central consequence, the 'instantaneous' effect of entanglement swapping in combination with statistical Bell-state detection seems to allow communication faster than light.

One important question still has to be discussed in order to complete the PSBA procedure: How does Bob know that Alice has sent him a message? In other words: When does Bob know that he can analyze the photon pairs of the next SCG for reading the next bit? A first, surely practicable solution is a fixed time interval Alice and Bob stipulated for synchronization purposes. After each time interval Bob reads one SCG (the term "polling" could be derived from computer science here) regardless of whether Alice has sent anything. If this SCG represents a set bit (1b), this could be interpreted as a previously agreed indicator for more transmitted data (following in the next SCGs). By putting more than two photons in an EG (and swapping the entanglement to different combinations of them), even the synchronization of this time interval could be realized. This approach probably works; however, it is not especially elegant, as potentially unnecessarily SCGs have to be consumed. For growing classical transmission distances (light weeks, light months or more) such a polling frequency can be slowed down proportionally while preserving the benefit of a faster transmission without heavily

loading Alice's and Bob's SCG pools.

Another, second variant would be more efficient (as no SCGs were consumed quasi-uselessly), but - if technically correct and realizable - this approach would be revolutionary. If we trust the delayed-choice experiments of [6] and [15], and interpret them correctly, Bob would not have to know when Alice sends data, but could analyze the photon pairs of one of his SCGs correctly at *any* point of time (as described above without additional (measurement) information from Alice), since the said experiments seem to show that he can analyze his photon pairs (1&4) correctly even *before* Alice executes BSM (or separable-state measurements) on her SCG's photon pairs. Hence, timing between Alice and Bob would no longer be necessary and Bob could read a new message starting at the next SCG whenever he tries, as long as Alice uses this SCG for transmitting a message at any point in the future. The author has doubts about whether this would be possible, but if it were, this would lead to the usual discussions about temporal paradoxes, since Bob could then read a message before Alice sends it.

### 3. Further Discussion And Conclusion

The concept of PSBA can be discussed in relation to several other technical approaches. The goal of quantum teleportation, for example, is to transfer one or more states from one particle to another particle. Several experiments like [7] have shown quantum teleportation over distances of more than 140 kilometers so far. Quantum teleportation needs additional information (via classical communication channels) to reconstruct the correct teleported states. Quantum teleportation represents information by a particle's states and uses entanglement for transportation. PSBA is different, because PSBA represents information by an entanglement and uses entanglement swapping for transportation. PSBA is also different, because PSBA does not need any additional classical information transport. As PSBA is a statistical approach (i.e. it uses a large number of particles), it has a lower efficiency regarding the density of encoded information (bits per particle) than quantum teleportation. Other approaches [16] use (concatenated) entanglement swapping for communication, but (similar to quantum teleportation) these approaches transport a particle's state over one (or more) entanglement swapping 'hops', while a PSBA communication path is built to be just one 'hop' long, since photons 1 and 4 are at the *same* communication participant. As other quantum teleportation approaches the approach proposed in [16] will also need additional classical communication to reconstruct the correct transferred state. Nevertheless, multi-hop PSBA communication is possible: Between two hops (at a 'repeater') the transmitted data has to be decoded and 'classically' transferred into another SCG of the next segment of the transmission route. Figure 8 shows the concept of concatenated entanglement swapping as described in [16]. Figure 9 on the following page

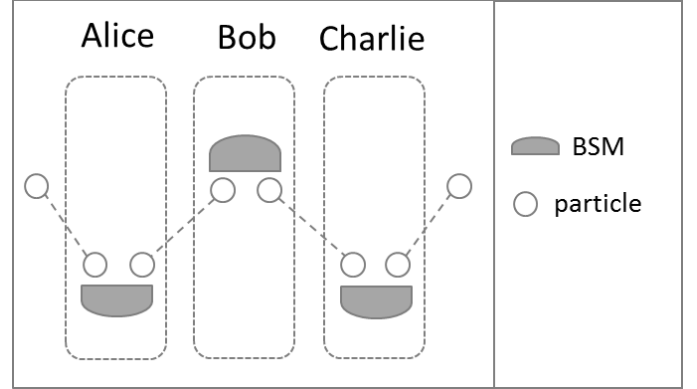


Figure 8: Concept of concatenated entanglement swapping protocol as described in [16]. Two photons of two entangled photon pairs are, in contrast to PSBA, spatially separated in an initial stage. With this approach a particle's state could be teleported over multiple hops and long distances. As for quantum teleportation, classical communication will be required to reconstruct the correct transferred states.

shows a multi-hop PSBA transmission of a binary 1 from Alice to Charlie.

PSBA also differs from approaches like Dense Coding [17, 18]), since for Dense Coding either a particle as one of two necessary carriers of 'parts of information' has to be sent to the receiver via classical ways, or measurement results have to be exchanged on classical ways. When using PSBA, entangled photons are distributed on classical ways as well, but no particles or measurement results are transmitted spatially *either during or after* encoding any information. For the same reason, PSBA differs from quantum secure direct communication protocols (QSDC) like [19, 20]. The focus of PSBA is the speed of transmission, so it would not be helpful to exchange measurement results on classical ways while communicating just for the purpose of security. As one can easily see, PSBA is compatible with Quantum Key Distribution (QKD) [14], as this encryption key will be generated (by using classical channels) before sending (encrypted) messages using PSBA. To realize QKD, Alice and Bob can take photon pairs from their EG pairs. The QSCD protocol presented in [20] is thus similar to PSBA, since Alice and Bob have shared two entangled particle pairs as well, but *both* Alice and Bob perform Bell-state measurements on their photons pairs (2&3), (1&4). In clear contrast to PSBA, in [20] the measurement results have to be announced on a classical way in order to enable Alice and Bob to decode the received messages.

Within this article a procedure called "Probabilistic Swapped-Bell-States Analysis" is proposed. PSBA seems to allow the transmission of information at a speed faster than light. To realize this, entanglement swapping is used as a transport channel where statistical detection of (swapped) entanglements is used for transmitting binary data. The PSBA approach has been discussed in relation to several existing approaches, such as quantum teleportation,

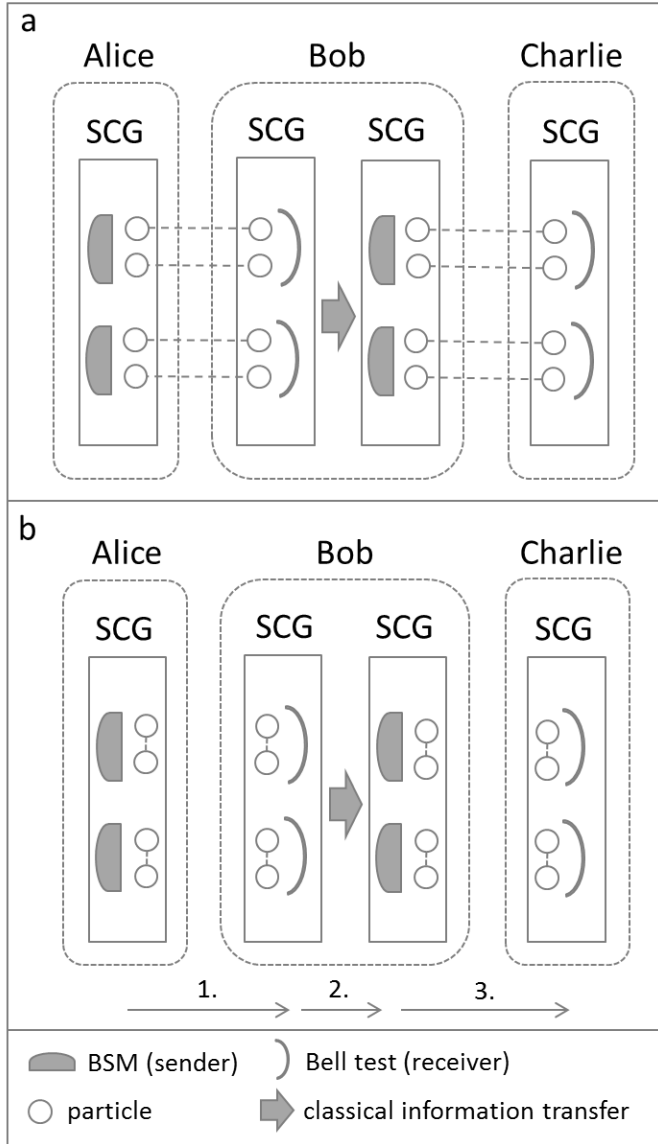


Figure 9: Multi-hop PSBA communication example. Without any loss of generality SCGs with *two* EGs were shown here as an example. Bob acts as a repeater in this scenario. The direction of transmission is from the left to the right (a): The initial state is shown: No entanglement swappings have been performed so far. (b): Transmission of the binary value 1b. Alice performs Bell-state measurements on all photon pairs in her current SCG (1.), which leads to entangled photons (2&3) at Alice and also at Bob's photon pair (1&4). Bob detects entanglements in his SCG and interprets this as a binary 1. Bob forwards this information by executing Bell-state measurements on an SCG which was entangled with another SCG at Charlie (3.). The communication using PSBA is limited to one transport 'hop'. Therefore after each hop the transmitted information has to be decoded from one SCG, transferred on classical ways to another SCG, and be re-encoded into the sending SCG of the next PSBA transport segment (Bob – Charlie). This is a local operation and as such it would take milliseconds on each repeater node in a multi-hop PSBA communication. For larger spatial transmission distances these milliseconds will have hardly any influence on the overall 'instantaneous' transmission.

'classical' (concatenated) entanglement swapping protocols, dense coding approaches as well as QKD and QSCD. An approach for multi-hop PSBA communication has been described. If PSBA mechanism should work, this would contradict essential parts of Albert Einstein's theory of relativity. In that case, as the author is not a quantum expert, these specialists will derive the consequences and show how PSBA can be implemented in the most efficient manner. The author has profound doubts about the correctness of the PSBA mechanism, since everything needed (mechanisms for detecting Bell states as well as the mechanism of entanglement swapping) has been known for more than 15 years; the author considers it improbable that not one quantum expert could have seen this possibility in this time. Hence the PSBA mechanism should be either incorrect or at least impracticable.

The author must thank several professors and PhD graduates of theoretical physics and optics who have invested time in answering the author's questions. The individual acknowledgements would follow in an update of this publication in case of confirmed relevance of this paper.

## References

- [1] A. Einstein, B. Podolsky, N. Rosen, Can quantum-mechanical description of physical reality be considered complete?, *Physical Review* (47) (1935) 777–780.
- [2] D. Salart, A. Baas, C. Branciard, N. Gisin, H. Zbinden, Testing the speed of 'spooky action at a distance' (2008). doi:10.1038/nature07121.
- [3] A. Peres, D. Terno, Quantum information and relativity theory, *Reviews of Modern Physics* 76 (1) (2004) 93–123. doi:10.1103/RevModPhys.76.93.
- [4] M. Żukowski, A. Zeilinger, M. Horne, A. Ekert, "event-ready-detectors" bell experiment via entanglement swapping, *Physical Review Letters* 71 (26) (1993) 4287–4290. doi:10.1103/PhysRevLett.71.4287.
- [5] J.-W. Pan, D. Bouwmeester, H. Weinfurter, A. Zeilinger, Experimental entanglement swapping: Entangling photons that never interacted, *Physical Review Letters* 80 (18) (1998) 3891–3894. doi:10.1103/PhysRevLett.80.3891.
- [6] Xiao-song Ma, Stefan Zotter, Johannes Kofler, Rupert Ursin, Thomas Jennewein, Časlav Brukner, Anton Zeilinger, Experimental delayed-choice entanglement swapping (2012).
- [7] X.-S. Ma, T. Herbst, T. Scheidl, D. Wang, S. Kropatschek, W. Naylor, B. Wittmann, A. Mech, J. Kofler, E. Anisimova, V. Makarov, T. Jennewein, R. Ursin, A. Zeilinger, Quantum teleportation over 143 kilometres using active feed-forward, *Nature* 489 (7415) (2012) 269–273. doi:10.1038/nature11472.
- [8] C. Schmid, N. Kiesel, U. K. Weber, R. Ursin, A. Zeilinger, H. Weinfurter, Quantum teleportation and entanglement swapping with linear optics logic gates, *New Journal of Physics* 11 (3) (2009) 033008. doi:10.1088/0031-8949/11/3/033008.
- [9] G. Weihs, A. Zeilinger, Photon statistics at beam-splitters: an essential tool in quantum information and teleportation, in: Perina J (Ed.), *Coherence and Statistics of Photons and Atoms*, J. Perina (Ed.), Wiley and Wiley, 2001.
- [10] P. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. Sergienko, Y. Shih, New high-intensity source of polarization-entangled photon pairs, *Physical Review Letters* 75 (24) (1995) 4337–4341. doi:10.1103/PhysRevLett.75.4337.
- [11] T. Jennewein, G. Weihs, J.-W. Pan, A. Zeilinger, Experimental nonlocality proof of quantum teleportation and entanglement swapping, *Physical Review Letters* 88 (1). doi:10.1103/PhysRevLett.88.017903.

## REFERENCES

- [12] P. Kwiat, H. Weinfurter, Embedded bell-state analysis, *Physical Review A* 58 (4) (1998) R2623–R2626. doi:10.1103/PhysRevA.58.R2623.
- [13] C. K. Hong, Z. Y. Ou, L. Mandel, Measurement of subpicosecond time intervals between two photons by interference, *Physical Review Letters* 59 (18) (1987) 2044–2046. doi:10.1103/PhysRevLett.59.2044.
- [14] C. Bennett, G. Brassard, Quantum cryptography: public key distribution and coin tossing (1984).
- [15] E. Megidish, A. Halevy, T. Shacham, T. Dvir, L. Dovrat, H. S. Eisenberg, Entanglement swapping between photons that have never coexisted, *Physical Review Letters* 110 (21). doi:10.1103/PhysRevLett.110.210403.
- [16] A. Khalique, W. Tittel, B. C. Sanders, Practical long-distance quantum communication using concatenated entanglement swapping, *Physical Review A* 88 (2). doi:10.1103/PhysRevA.88.022336.
- [17] C. Bennett, S. Wiesner, Communication via one- and two-particle operators on einstein-podolsky-rosen states, *Physical Review Letters* 69 (20) (1992) 2881–2884. doi:10.1103/PhysRevLett.69.2881.
- [18] K. Mattle, H. Weinfurter, P. G. Kwiat, A. Zeilinger, Dense coding in experimental quantum communication, *Physical Review Letters* 76 (25) (1996) 4656–4659. doi:10.1103/PhysRevLett.76.4656.
- [19] K. Boström, T. Felbinger, Deterministic secure direct communication using entanglement, *Physical Review Letters* 89 (18). doi:10.1103/PhysRevLett.89.187902.
- [20] Y. Hyung Jin, H. Chang Ho, L. Jong In, K. Ji In, Two way quantum direct communication protocol using entanglement swapping, *Journal of the Korean Physical Society* 56 (6) (2010) 1733. doi:10.3938/jkps.56.1733.